The Structure of Team Search Behaviors with Varying Access to Information

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Abstract

In many team-based activities, members search for information to gain situational awareness and thereby structure their own behavior. The extent to which members are coupled and in control of their surrounding environment can be accessed via the fluctuations of their searching behaviors. To facilitate prospective control, assistive technologies such as a head-up display (HUD) can alleviate the demands of search and facilitate team performance. This study investigated how three-person teams divided their labor and structured their search behavior when playing a multiplayer search-and-retrieval task where first-person visibility and access to a HUD were manipulated. Results showed that access to task relevant information facilitated performance and division of labor, and increased prospective control of searching behaviors, as indexed by detrended fluctuation analysis (DFA). Over multiple sessions, teams learned to use the HUD to structure their behavior to achieve the task goal. Results indicate the potential in using DFA for monitoring prospective control in team contexts.

Keywords: team coordination; detrended fluctuation analysis; head-up display; search behaviors; multiplayer video game

Introduction

In many task contexts, teams perform more efficiently than individuals due a team's ability to divide labor. For such divisions of labor to be successful, team members must effectively coordinate their actions in space and time, as well adopt specific roles or responsibilities. The challenge, however, is ensuring that team members have sufficient information to coordinate their actions with those of the team and the goals of the task. For instance, in sports such as soccer, players constantly scan their environments to assess their own position in relationship to their teammates, the ball, and opposing players, as well as to determine what actions are afforded both now and in the future (Araujo, Davids, & Hristovski, 2006; Silva et al., 2013). Accordingly, teams whose members exhibit greater visual-search behaviors perform better (Jordet, Bloomfield, & Heijmerikx, 2013; Phatak & Gruber, 2019). The extent to which individuals must perform search behaviors to enable effective team coordination is also context dependent. For example, a soccer player's role, field position, whether they have the ball, and phase of play all modulate the degree of visual-search behaviors a specific team member must engage in to maximize team performance (McGuckian et al., 2020).

The effective detection of task-relevant information facilitates team coordination and performance by ensuring team members maintain robust levels of situational awareness. This enables team members to act prospectively (act based on perceived future expectations) and effectively adapt to task perturbations. Importantly, the extent to which individuals maintain strong situational awareness can be determined via the structure of their search behavior. Specifically, the patterns of behavioral variability individuals exhibit during a task can indicate the degree to which their behavior is *self-directed* or prospectively adapting to task or environmental events versus *other-directed* or reactive to task or environmental events (Van Orden, Kloos, Wallot, 2011). These patterns can be assessed using *Detrended Fluctuation Analysis* (*DFA*), which indexes the degree to which the patterning of behavioral fluctuations is random, persistent (prospective), or anti-persistent (reactive) across timescales (Washburn et al., 2015).

Importantly, an individual's ability to behave prospectively is also task- and experience-dependent. In foraging tasks, for example, the structure of search behavior is dictated by the availability of food sources (Raichlen et al., 2014; Sims et al., 2012). As infants age, their gaze behavior becomes more self-directed and persistent (Stallworthy et al., 2020). In tasks which require sensitivity to perturbations, like surgery, experts exhibit less persistent structure (Uemura et al., 2014). Additionally, in cooperative contexts, the structure of the variability of individuals is found to converge (Rigoli et al., 2020) which may enable greater information flow between individuals (West, Geneston & Grigolini, 2008).

Current Study

The 21st century is defined by sociotechnical systems whereby assistive technologies can aid individuals in facilitating team coordination (Fiore & Wiltshire, 2016). An example of such technology is *Head-Up Displays* (*HUDs*). While already employed in flight and vehicle control systems (Charissis, Papanastasiou, & Vlachos, 2008; Rafi et al., 2018; Smith et al., 2015; Sojourner & Antin, 1990; Ververs & Wickens, 2000), the most widespread use of HUDs is in single and multiplayer video games. The use of HUDs provides individuals immediate access to task-relevant information thereby reducing the need for information search (Zammitto, 2008). Indeed, research by Caroux and Isbister (2016) found that both Real Time Strategy and First-Person Shooter players spent significant time utilizing in-game HUDs, which facilitated awareness of the game environment. HUDs can thus be a useful source of task-relevant information, enabling individuals to act prospectively and facilitate team coordination. In their simplest form, HUDs can provide an 'eye-in-the-sky' view, giving individuals global, task-relevant information.

The current study explored the use of HUDs as an assistive technology to enable greater situational awareness by individual players. The study explored how access to global, task-relevant information versus a local, first-person point of view structured the behaviors of individuals in a team search-and-retrieval task. Task difficulty was also manipulated (using 'fog') to obscure access to task-relevant information. We expected that having access to global HUD information would allow team members to behave more prospectively when completing the task. Furthermore, in more difficult conditions (i.e., in fog and/or without the HUD), players would exhibit less persistent and more reactive search behavior.

The study also explored whether access to global task-relevant information (via a HUD) resulted in better team coordination and performance. Specifically, we explored whether access to the HUD afforded a more coordinated division of labor between team members, allowing them to better partition the task space (i.e., decrease the overlap in player search areas).

Finally, teams completed the search-and-retrieval task over four sessions to examine the effects of experience on team coordination and the prospective nature of search behavior.

Method

Participants

Thirty individuals (16 female, 14 male) were pseudo-randomly selected to participate in the study. Individuals were placed into ten three-person teams. Teams consisted of at least one female (5 teams with 1 female; 4 teams 2 females; 1 team 3 females). Participants were 18 to 45 years of age (M = 23.19, SD = 4.71) and either native (N = 24) or fluent (N = 6) English speakers. All participants completed the experiment remotely online using their own personal/home computer (gaming experience was recorded but not reported here). Participants received $30 AUD for each session, and a bonus $40 AUD for completing all four sessions with the potential to receive another $50 AUD if their team was deemed to have the best performance in Session 4. The study was approved by the Macquarie University Institutional Review Board.

Materials and Design

Multiplayer Game. Across all sessions, teams played a networked multiplayer game referred to as *Desert Herding*. The game was designed using the Unity3D Game Engine (Version 2018.4 LTS; Unity Technologies, San Francisco, CA). Participants downloaded a standalone version of the game and connected to the experiment server, which was hosted on Amazon Web Services EC2 with Windows 10. The server recorded all game state data at a 90-Hz sample rate. In addition to interacting with each other in-game, participants could verbally communicate via the use of internet teleconferencing software (Zoom; San Jose, California).

The game involved locating, corralling, and containing a set of *Target Agents* (TAs) who roamed about a large area of desert terrain (500 × 500 m in game space). The goal of the game was to contain the TAs within a fixed central location (Fig. 1e) measuring 10 m in diameter. Participants interacted with the TAs by controlling their own humanoid game avatar (Fig. 1c). Participants controlled their avatars using a mouse and the 'W', 'A', 'S', and 'D' keys on their keyboard.

Each trial terminated and feedback about a team's successful performance was provided whenever all TAs were corralled within the containment area for 5 continuous seconds; otherwise, the trial would terminate after 5 minutes with feedback about the team's failure. At the start of each session, and between each trial, participants' avatars were placed in a 'lobby' overlooking the game field (Fig. 1a) for 10 s. This lobby contained a display screen showing how many trials were completed, the numbers of successes, and failures.

When a trial began, participants' avatars were randomly placed within 100 m of the containment location, while TAs were randomly placed within 180 m of the containment location (Fig. 1b). When unperturbed, the TAs exhibited Brownian motion dynamics: a random force between 0 to 60 N was applied to the TA in a random (x, y) planar direction at a rate of 1 Hz (TAs had 1 kg mass). When a participant's avatar was within 10 m of a TA, an additional repulsive force was applied, moving the TA away from the avatar. This force was inversely proportional to the distance between the avatar and the TA (maximum force = 450 N). The Brownian and repulsive forces were applied until the TA reached a maximum velocity of 10 ms^{-1}.

The TAs provided visual feedback about their status by changing color; the ring around their middle was orange when the TAs were unperturbed (and hence exhibiting Brownian motion), red when fleeing an avatar, blue if contained, and green when all TAs were contained (Fig. 1d).

Task Manipulations. Three manipulations were employed: (1) *target number*, or the number of targets that had to located, corralled, and contained (9 vs. 18); (2) *visibility* within the game environment (fog vs. no fog); and (3) *type* of information (local vs. global) provided by the HUD. In the absence of fog, participants had near perfect visibility and could see >150 m (Fig. 1e); with fog, visibility was restricted to approximately 10 m (Fig. 1f). The HUD provided either local information about only the cardinal heading of a participants' avatar (Fig. 1g) or *global* information (Fig. 1h) about the relative location and heading of all avatars and TAs, including the TAs 'state' (color). The HUDs always indicated the containment location as a landmark.

For each session, teams completed two blocks, each consisting of 8 trials representing all possible combinations of the task manipulations (*Target Number, Visibility, HUD*). For the first three sessions, trial order for each block was pseudo-randomized. For the fourth and final session, all teams completed the same random trial order.

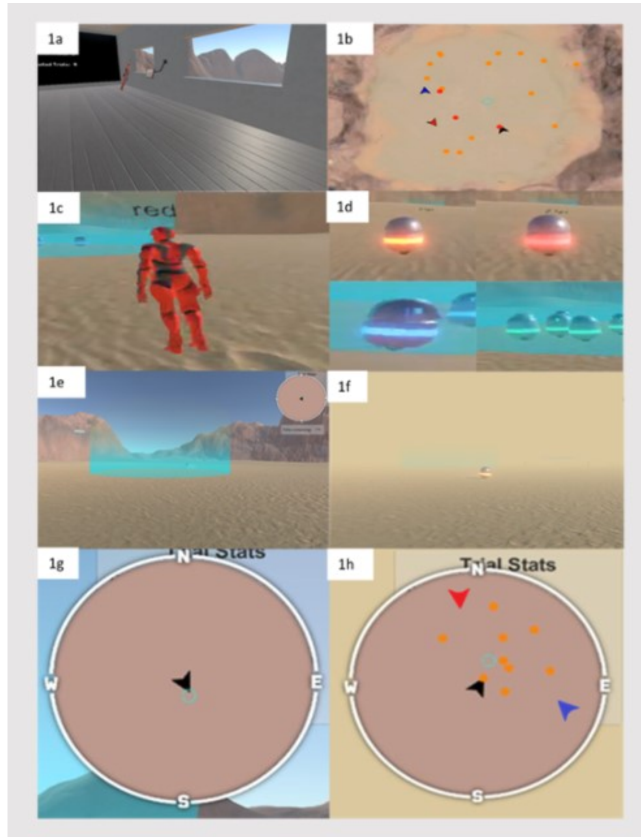

Figure 1: Task Environment & Experimental Manipulations. See text for details.

Procedure

Prior to the study, participants were notified via e-mail about their four allocated session times and asked to give informed consent, provided links to download the game and both general task and session instructions. Each participant in a team was assigned a color (red, blue, or black) which served as their name and avatar's color during the trials.

Approximately one hour prior to a team's session, participants received an e-mail containing the link to the Zoom meeting. Participants were then asked to join an audio (only) meeting 10 minutes prior to the scheduled session time. For the experiment, an audio file was recorded for each participant and for all participants in the team. This data was not analyzed here but was recorded for the purposes of a larger study (see Discussion for more details).

Each session lasted for a maximum of 90 minutes and participants were asked to complete as many of the 16 trials as they could within that period. After completing all trials or the session time had elapsed, the Zoom call and experimental session ended. This procedure was followed for all sessions.

Design and Measures

Only performance during the first and last session was analyzed. Target number did not affect the pattern of results and is thus not reported here. The analysis used a 2 (*Session*: 1, 4) × 2 (*Visibility*: no-fog, fog) × 2 (*HUD*: local, global) repeated-measures design. All completed trials were analyzed (i.e., successful, and unsuccessful) and all measures were calculated for teams, averaged across trial blocks.

Task Performance. Task performance was measured in two ways. The first measure, *trial duration*, was the mean length of the trial in seconds. The second measure was the *proportion of TAs contained* during the last 5 s of a trial.

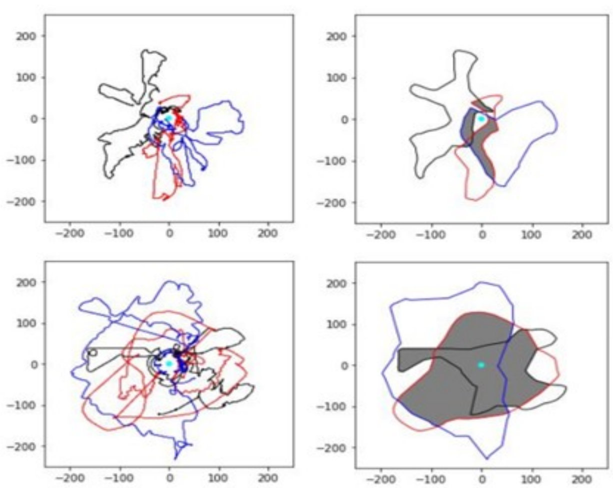

Figure 2: Exemplars of low (top panels: 12% overlap, 18/ No Fog/Global HUD) and high overlap (bottom panels: 54% overlap, 9/Fog/Local HUD) from one team. Left panels show raw movement data of players throughout a trial; right panels show calculated polygons for players with gray regions showing overlap.

Participant and Team Behaviors. Two measures were identified to assess behaviors at the individual and team levels. At the individual level, the persistent structure of participants' movement dynamics during search and containment was quantified using DFA (Peng et al., 1994; Hardstone et al., 2012). Specifically, differences in the displacement direction of participants' movement timeseries (down-sampled to 5 Hz) was submitted to DFA using the *nolds* python toolbox[1]. This analysis generates a measure DFA_α, wherein $DFA_\alpha = 0.5$ indicates random fluctuations in participant displacement behavior across time, akin to white noise, $DFA_\alpha = 1.0$ reflects moderately persistent behavioral fluctuations, akin to pink noise, and $DFA_\alpha = 1.5$ reflects highly persistent behavioral structure, akin to Brownian motion. Accordingly, for the present task, changes in DFA_α, either across session or between task conditions, measured changes in the persistence of player displacement behavior (i.e., higher DFA_α = more persistent behavioral dynamics), with an increase in DFA_α reflecting an increase of *prospective control* (Van Orden et al., 2011).

Team coordination was quantified by the degree of overlap between players' search areas; referred to as *proportion search overlap*, with participant search areas defined as the bounding polygon which best encapsulated a participant's movements (down-sampled to 1 Hz). Participant search-area polygons were created using the *alphashape* toolbox[2]. (See Figure 2 for an illustration of how this was calculated.)

Results

All post-hoc analyses were conducted using a Bonferroni correction. A full listing of the means and SD for each DV as a function of condition are listed in Table 1.

Table 1: Condition Means and SDs as a function of Session, Visibility and HUD.

DVs		No Fog				Fog			
		Local HUD		Global HUD		Local HUD		Global HUD	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
A	S1	.60	.27	.63	.38	.18	.26	.65	.43
	S4	.88	.21	.98	.08	.38	.27	.85	.21
B	S1	245	37	228	48	289	20	243	41
	S4	191	33	164	28	275	22	191	40
C	S1	.80	.19	.79	.24	.54	.26	.73	.39
	S4	.98	.03	1.00	.00	.80	.17	.97	.07
D	S1	.24	.12	.22	.08	.31	.08	.15	.04
	S4	.13	.06	.09	.06	.28	.10	.14	.09
E	S1	.57	.04	.58	0.04	.58	.04	.60	.03
	S4	.61	.03	.63	0.04	.61	.04	.62	.03

Note: Dependent Variables (*DV*s): *A* = success rate; *B* = trial duration; *C* = proportion contained; *D* = proportion overlap; *E* = DFA_α.

Trial Duration. There were significant main effects of Session [$F(1,9) = 90.23$, $p < .001$, $\eta_p^2 = .91$], Visibility [$F(1,9) = 55.06$, $p < .001$, $\eta_p^2 = .86$], and HUD type [$F(1,9) = 49.97$, $p < .001$, $\eta_p^2 = .85$], with teams completing trials in less time in Session 4, when visibility was unimpaired and when they had access to the global HUD. The analysis also resulted in significant two-way Session × Visibility [$F(1,9) = 8.85$, $p = .016$, $\eta_p^2 = .50$] and Visibility × HUD [$F(1,9) = 27.06$, $p = .001$, $\eta_p^2 = .75$] interactions, and a three-way Session × Visibility × HUD interaction [$F(1,9) = 6.34$, $p = .033$, $\eta_p^2 = .41$].

Given the three-way interaction, separate 2 (Visibility) × 2 (HUD) simple-interaction analyses were conducted for each Session. For Session 1, this analysis revealed main effects of Visibility [$F(1,9) = 11.87$, $p = .007$, $\eta_p^2 = .57$] and HUD [$F(1,9) = 10.10$, $p = .011$, $\eta_p^2 = .53$], and a significant Visibility × HUD interaction [$F(1,9) = 15.67$, $p = .003$, $\eta_p^2 = .64$], with the global HUD significantly reducing the impact

[1] https://pypi.org/project/nolds/

[2] https://pypi.org/project/alphashape/

of low visibility (fog) on trial duration, compared to the local HUD condition ($p < .01$). For Session 4, there were significant main effects of Visibility [$F(1,9) = 107.31$, $p < .001$, $\eta_p^2 = .92$] and HUD [$F(1,9) = 77.06$, $p < .001$, $\eta_p^2 = .90$], and a significant Visibility × HUD interaction [$F(1,9) = 23.30$, $p = .001$, $\eta_p^2 = .72$]. Post hoc analysis revealed that the global HUD facilitated performance more in both full ($p < .01$) and impaired visibility conditions ($p < .01$) compared to the local HUD conditions, suggesting that, with practice, teams learned to better utilize the global HUD effectively.

Proportion of Targets Contained. There was a significant main effect of Session [$F(1,9) = 11.44$, $p = .008$, $\eta_p^2 = .56$] where, on average, teams contained a significantly higher proportion of targets during Session 4 compared to Session 1. There were also significant main effects of Visibility [$F(1,9) = 11.82$, $p = .007$, $\eta_p^2 = .57$] and HUD [$F(1,9) = 14.35$, $p = .004$, $\eta_p^2 = .62$] with greater visibility and/or access to the global HUD resulting in more targets being contained. A Visibility × HUD interaction was also found [$F(1,9) = 39.36$, $p = .001$, $\eta_p^2 = .81$]. There was no significant difference between local and global HUD conditions in the proportion contained when there was no fog ($p > .05$). But when fog was present, teams contained significantly more targets in the global HUD condition compared to the local HUD condition ($p < .01$), further indicating that the global HUD provided teams with enough information to mitigate the visual deficit caused by the fog.

DFA$_\alpha$. The analysis of DFA$_\alpha$ revealed significant main effects of Session [$F(1,9) = 12.78$, $p = .006$, $\eta_p^2 = .59$] and HUD type [$F(1,9) = 17.78$, $p = .002$, $\eta_p^2 = .66$], with participants exhibiting more persistent movement patterns with both practice and when given access to the global HUD. There was also a Session × Visibility interaction [$F(1,9) = 8.64$, $p = .02$, $\eta_p^2 = .49$]. Post-hoc analysis revealed that teams exhibited more persistent search behaviors when fog was present for Session 1 ($p < .05$) while Visibility did not differentiate search behaviors in Session 4.

Proportion Overlap in Participant Search. There were significant main effects of Session [$F(1,9) = 36.97$, $p < .001$, $\eta_p^2 = .80$], Visibility [$F(1,9) = 28.92$, $p < .001$, $\eta_p^2 = .76$], and HUD [$F(1,9) = 38.33$, $p < .001$, $\eta_p^2 = .81$], with players overlapping less in their search area in Session 4, when visibility was unimpaired and when participants had access to the global HUD. Session × Visibility [$F(1,9) = 14.88$, $p = .004$, $\eta_p^2 = .62$] and Visibility × HUD [$F(1,9) = 18.16$, $p = .002$, $\eta_p^2 = .67$] interactions were also observed. Post-hoc analysis revealed that teams had more overlap in their search areas in Session 1 compared to Session 4 in the no-fog conditions ($p < .01$), but not in the fog conditions ($p > .05$). This suggests that, with practice, teams became better at partitioning the task space in the no-fog condition, but not in the fog condition. Furthermore, there was no significant difference in proportion overlap between local and global HUD conditions in the no-fog condition ($p > .05$), but the global HUD resulted in less overlap than the local HUD ($p < .01$) in fog trials.

Relationship between Participant Behavior and Performance. To understand how participant behavior influenced team performance, an analysis was conducted to determine if the structure of participants' search behavior (via DFA$_\alpha$) and the extent to which their search areas overlapped impacted team performance across task conditions. More specifically, this analysis considered whether increases in the persistence or prospective nature of participant movements (i.e., increases in DFA$_\alpha$) and decreases in the amount of *player overlap* were related to improvements in task performance. To explore these relationships, standard regressions (correlations) were conducted to determine the magnitude of covariance between average participant (i.e., team) DFA$_\alpha$ and player overlap with respect to trial duration and the proportion of targets contained.

Regarding the proportion of overlap in participants' search, the analysis showed that the degree to which participants' search areas overlapped also covaried with how long teams took to complete the trials in the no-fog/local [$\beta = 230.11$, $R^2 = .56$, $p < .05$] condition in Session 1, and in the no-fog/local [$\beta = 426.18$, $R^2 = .41$, $p < .05$] and fog/global [$\beta = 376.92$, $R^2 = .73$, $p < .01$] conditions in Session 4, with less player overlap leading to faster task completion (i.e., better performance). When predicting the proportion of targets contained, the amount of player overlap covaried with the proportion of targets contained in the no-fog/local [$\beta = -1.21$, $R^2 = .60$, $p < .01$] and fog/local [$\beta = -2.21$, $R^2 = .49$, $p < .05$] conditions in Session 1, and the fog/global [$\beta = -0.68$, $R^2 = .68$, $p < .01$] condition in Session 4.

Regarding DFA$_\alpha$, the analysis revealed that the persistence of participant movement only negatively covaried with how quickly teams finished a trial during the no-fog/global condition [$\beta = -814.32$, $R^2 = .42$, $p < .05$] in Session 1. However, DFA$_\alpha$ did negatively covary with trial duration in Session 4 for all but the most difficult task configuration (fog/local) [$\beta = -1160.6$ to -584.779, $R^2 > .45$, $p < .05$], with those teams/participants that exhibited more persistent movements (i.e., higher DFA$_\alpha$ values) completing trials across those conditions significantly more quickly. Similarly, DFA$_\alpha$ significantly covaried with the proportion of targets teams could contain when global HUD information was available [no-fog/global $\beta = 0.16$, $R^2 = .47$, $p < .05$; fog/global $\beta = 1.799$, $R^2 = .55$, $p < .05$], and marginally significant when there was no-fog/local HUD information [$\beta = 0.591$, $R^2 = .39$, $p = .054$], during Session 4. No significant relationship was found for Session 1. Collectively, these regressions provide support that more persistent and prospective participant behavior did afford better task performance.

Conclusion

This study explored the use of a HUD to facilitate team coordination using a dynamic, multiplayer search-and-retrieval task. The results indicated that greater access to task-relevant information, either via the HUD or via an unobscured first-person field of view, afforded greater prospective control of behavior by team members, as well as a more effectively coordinated division of labor. Furthermore, as teams gained experience with the task, players appeared to learn to utilize the HUD to structure their behavior more efficiently. However, ease of access to task-relevant information did not necessarily equate to greater overall task performance. Rather, the results indicated that there are diminishing returns of HUDs when a player's first-person view is unobscured.

Importantly, the results indicate that the relationship between the attunement of task-relevant information and the prospective control of action (Van Orden, Kloos & Wallot, 2001; Washburn et al., 2015) extends to the dynamics of team member behaviors in digital, multiplayer contexts. Thus, the use of DFA to index player control may also be a useful signal to monitor in team tasks to assess task difficulty or player fatigue. Finally, although the use of HUDs may facilitate team coordination, the role verbal communication has on facilitating team coordinative performance in such environments is less known. Understanding the interplay between team communication and assistive technologies such as HUDs have on team coordinative performance is less understood. For instance, an unintended consequence of making team members over reliant on such assistive technologies as HUDs may be a reduction in team verbal communication, potentially hindering team coordination. Thus, future work should monitor the behaviors of team members and design training methodologies to enable the effective use of assistive technologies while also maintaining resilience in case of technological failure (Gorman, Cooke, & Amazeen, 2010).

Acknowledgements

This work was supported by the Australian Department of Defence, Science and Technology (DST) group (partnership grant MyIP8655) and Human Performance Research Network (HPRnet, partnership grant ID9024).

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